AMERICAN JOURNAL OF PHYSICAL ANTHROPOLOGY 108:261–268 (1999)

Determination of Age at Death: Assessment of an Algorithm of Age Prediction Using Numerical Three-Dimensional CT Data From Pubic Bones

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KEY WORDS age estimation; human osteology; forensic; quantification; invariant descriptors

ABSTRACT The determination of age at death is an important part of physical and forensic anthropology. Because of resistance to decomposition and the simplicity/accuracy ratio, the direct observation of the os pubis by Suchey-Brooks phase analysis is the preferred reference system for determination of age at death. We propose an age-prediction system using a pubic symphysis numerical database obtained from CT x-ray through quantification of age-linked parameters. Our system increases the accuracy of age estimation and at the same time preserves the integrity of the archeological material. Am J Phys Anthropol 108:261–268, 1999.

The determination of age at death is an important part of physical and forensic anthropology. Because of their resistance to decomposition and lifelong metamorphosis, bones and teeth are the best materials for age estimation (Todd, 1920; Brooks, 1957; McKern and Stewart, 1957; Kerley, 1965; Iscan et al., 1985; Bass, 1987; Lamendin et al., 1992). The pubic symphysis is often examined because it is well preserved against postmortem physical damage. In addition, use of the symphysis yields a high simplicity/accuracy ratio among age estimation methods. The direct observation of the os pubis by the Suchey-Brooks phase analysis method, which requires comparison of the bone surface to reference casts, is one of the most interesting systems used (Fig. 1) (Meindl et al., 1985; Suchey et al., 1986; Katz and Suchey, 1986; Brooks and Suchey, 1990). However, this age-determination method lacks precision, especially in individuals over 40 years (width of the 95% confidence interval for males, phase I: 15–23; phase II: 19–34; phase III: 21–46; phase IV: 23–57; phase V: 27–66; phase VI: 34–86) (Suchey et al., 1979). Furthermore, it involves a long and difficult process to obtain well-prepared bones without damaged anatomical parts.

The goal of this study is to improve the accuracy of age estimation at death and at the same time preserve the integrity of the archeological material through the analysis of pubic bone numerical images.

MATERIALS AND METHODS

Experimental strategy

Computed tomography x-ray, which is extremely efficient in the study of bone, was selected to compile a pubic symphysis numerical database that we could search for quantifying age-linked parameters. An algorithm for age prediction using these variables (de-

Grant sponsor: Projet Hospitalier de Recherche Clinique du Ministère Français de la Santé.

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Received 26 March 1998; accepted 11 November 1998.

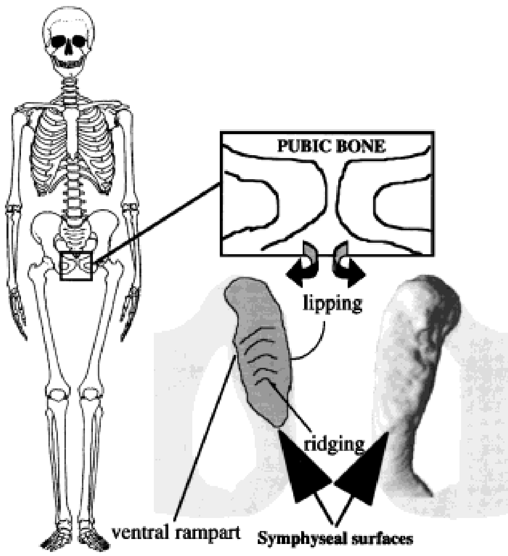

Fig. 1. The pubic bone consists of a right and left symphyseal surface. Location of key age changes studied in this work—lipping, ridging and progression of ventral rampart—are indicated in this figure.

fined below) is proposed, and its accuracy is compared to the Suchey-Brooks method.

The collection of documented pubic bones. The forensic medicine department of Brest collected 300 adult pubic bones between 1990 and 1994, each well-documented for sex and age at death. The differentiation between female and male pubic bones is easy to make. Because the results of using the female symphysis were worse using the Suchey-Brooks method, we conducted a male analysis and studied a random sample of 74 pubic bones.

The numerical data base. On an Elscint Exel 2400 CTscan (Elscint, Tel Aviv, Israel), longitudinal sections of each of the 74 male left and right symphyseal surfaces of the sample were completed every millimeter (about 30 sections per symphysis). The scan parameters consisted of a field of view of 350 mm, a zoom of 1.1, an image matrix of 512 $\times$ 512 pixels; thus, the resolution obtained was about 0.5 mm/pixel.

Classification of the 74 male pubic symphysis using the Suchey-Brooks method A blind macroscopic analysis of the 74 pubic bones was carried out by a well-trained expert in the Suchey-Brooks method in order to classify each pubic bone into one of the six phases, with comparison to the 12 reference commercialized casts (France Casting Trademark, Bellvue, CO). For the Suchey-Brooks method, the estimated age was considered as the mean age of the obtained phase. These mean values were calculated using the pubic symphyses from our collection.

Selection and quantification of age-linked parameters from numerical images Quantitative analysis of key age changes of the pubic bone stressed by Suchey and Brooks involved the following features.

1. Lipping. The lipping of the dorsal border is an important distinguishing feature for the fourth and fifth phases of the Suchey-Brooks classification. Its quantitative analysis was performed using a horizontal selected section and by measuring interactively the angle between the dorsal border and the symphyseal surface. The value of this angle is in inverse ratio to lipping (Fig. 2C).
2. Ridging. The symphyseal face has a billowing surface (horizontal ridges and furrows) in the first phases of the Suchey-Brooks classification. The symphyseal face becomes progressively smooth with age. To quantify ridging, we measured the amplitude and the period of the sine curve corresponding to the billowing surface of the symphysis. Using a frontal section perpendicular to ridging, a discrete monodimensional signal formed by a selection of points belonging to the side view surface was extracted. Ridging was quantified by the amplitude and frequency of a peak identified on the discrete Fourier transform of this monodimensional signal (Fig. 2A).
3. Ventral rampart in extension from the lower extremity. This is a distinguishing feature of the four initial phases of the Suchey-Brooks classification. Its measurement, expressed as a percentage of the symphysis face length, was interactively measured using 3-D volume rendering images (Fig. 2D).

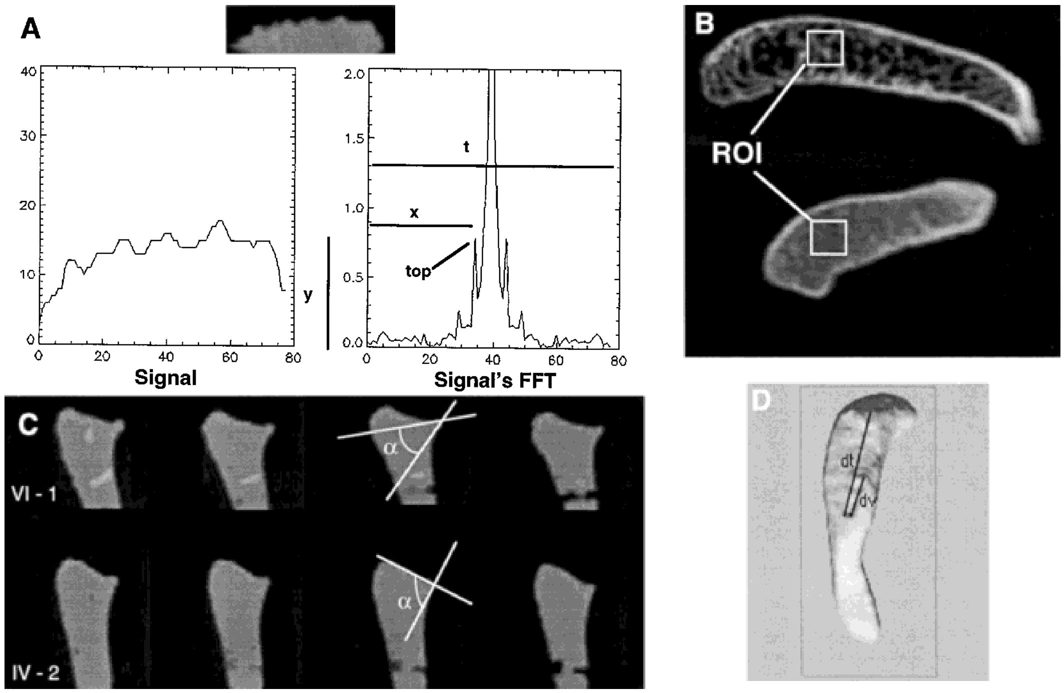

Fig. 2. Examples of interactive measurements of key age changes. **A:** Amplitude (amplitude of ridging (y) in millimeters) and frequency (=((t/2) -x)/t) of ridging calculated on a fast Fourier transform (FFT) of selected points signal belonging to the surface above. **B:** Bone density characterized by the mean and by standard deviation of the gray-level scale (0–256) computed on a region of interest (ROI) of the trabecular bone. Phase VI (upper) and I (lower) of the Suchey-Brooks classification. **C:** Measurement of lipping angle (angle of lipping (α in degrees): upper phase VI and lower phase IV of the Suchey-Brooks classification. **D:** Measurement (in percent) of ventral rampart construction (dv) normalized by symphyseal surface size (dl).

Thanks to the 3-D numerical database, it was possible to study additional parameters which were not available from the macroscopic bone analysis. Quantitative analysis of other age-linked parameters included the following.

1. Texture of the trabecular bone (Fig. 2B). It is accepted that the trabecular bone changes with age. In the first decade, the individual trabeculae are continuous interconnecting or branching bands; then atrophic trabeculae appear as struts, bars, or blots with a reduction in the mean trabecular density. We studied trabecular bone using a longitudinal section of the pubic symphysis with a density window between −1,000 and +500 units-Hounsfield. We measured the mean and standard deviation of the gray-level distribution using a region of interest selected in the trabecular bone.
2. Distances measured using invariant descriptors for gray-level images (Fig. 3). Some key age changes of the pubic bone stressed by Suchey and Brooks are not easy to quantify. Indeed, they consist of complex morphological features, which require for quantification a global comparison system to a reference; therefore, we have measured distances to the casts, selected as references, using invariant descriptors for gray-level images. The computed tomographic longitudinal sections are nearly parallel to the symphyseal surface which is practically contained in a plane, the equation of which we determined using a least-squares fitting technique. We set this reference plane close to the symphyseal surface.

Then we projected the symphysis face on this reference plane. On each point of the

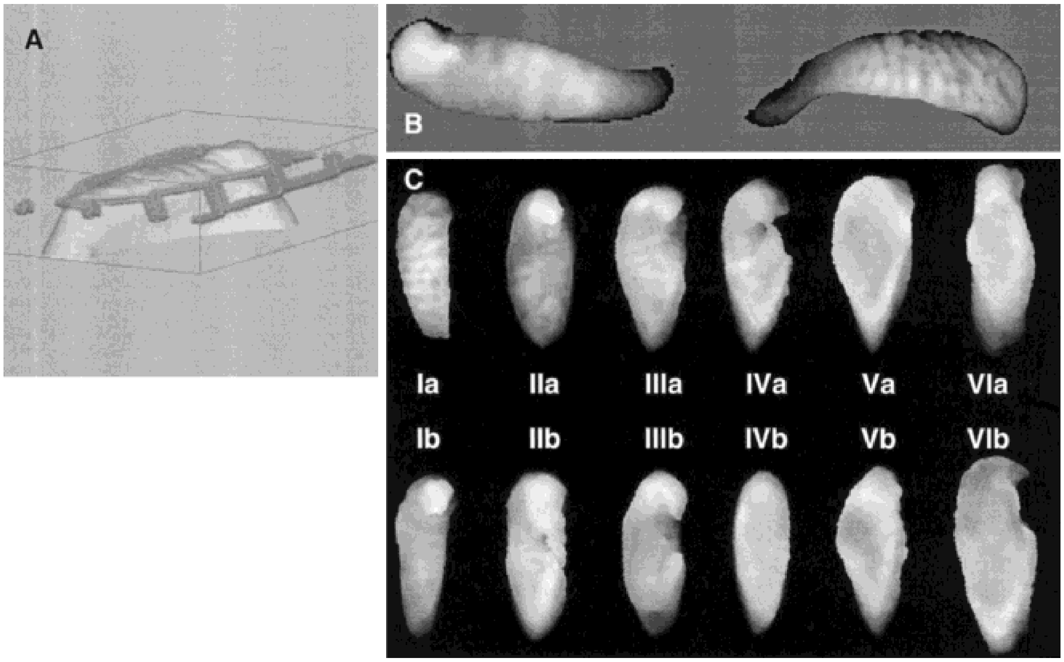

Fig. 3. Measurement of morphological distances between a symphyseal surface and each one of the 12 reference casts of the Suchey-brooks method. **A:** Setting of a reference plane parallel to the symphyseal surface. **B:** Depth image obtained by projection on this plane. The gray level in each point depends only on the orthogonal distance with projection on the reference plane. **Left:** Example of phase II. **Right:** Example of phase I. **C:** Depth images of the 12 reference casts. All depth images were described with invariant descriptors (I_f) with respect to translation, rotation, and scaling descriptors established from the coefficients of Fourier-Mellin transform ($M_f(k,v)$):

$$M_f(k, v) = \int_0^{+\infty}\int_0^{2\pi} f(r, \theta)e^{-ik\theta}\, r^{-iv}\,\frac{dr}{r}\,d\theta$$

$$\begin{cases} I_f(0, 1) = |M_f(1, 1)|[M(0, 1)]^{-1} \\ I_f(k, s = 1 + iv) = M_f(k, s)[M_f(1, 1)]^{-k}\,|M_f(1, 1)|^{k}\,[M(0, 1)]^{-s} \end{cases} \qquad \text{(Equation 1)}$$

Comparison of two depth images with $d_2(F,G)$ using the invariant descriptors of each one. We provided 12 distances for each symphyseal surface studied by comparison with 12 reference casts of the six-phase Suchey-Brooks classification.

$$\mathrm{d}_2(F, G) = \left(\sum_{k\in Z}\sum_{v\in R}\left(|I_f(k, \sigma_0 + iv)| - |I_g(k, \sigma_0 + iv)|\right)^2\right)^{1/2} \qquad \{\text{Equation 2}\}$$

resulting computed image, the gray level was in ratio to the orthogonal distance between the corresponding point of the symphyseal surface and the reference plane.

We chose invariant descriptors with respect to translation, rotation, and scaling to characterize these images of projection. These descriptors were established from the coefficients of a Fourier Mellin transform of the gray-level distribution (Ghorbel, 1994). Thus, a distance between two images, their similarity testing, was defined from these invariant descriptors and used to compare an unknown symphysis with the 12 reference casts of the Suchey-Brooks method. The 12 distances were studied as age-linked parameters.

For all these above computations, the software used was written in C language and was specially developed for Vax Computer.

Statistical analysis

All analyses were performed on the working sample of 148 symphyseal surfaces (the right and left one for each of the 74 pubic

symphyses). First, we looked for a relationship between age and any of the above selected variables using an univariate linear regression analysis. Second, a multiple linear regression analysis was applied to these variables for the 148 left and right symphyseal surfaces. In order to optimize the results obtained, we stratified the 148 symphyseal surfaces into two groups according to the first step of the macroscopic analysis: the search for a ridging (peak amplitude: $\leq$0.05 mm or $>$0.05 mm). Then we proposed an age-prediction system using data from the right and left symphyseal surfaces. For each right and left surface, a multiple linear regression analysis applied to the remaining symphyseal surfaces provided an adjusted predicted age. Thus, for each pubic symphysis we obtained two 95% confidence intervals corresponding to the right and left symphyseal surfaces; the mean value of these two intervals intersection was considered as the final estimated age at death. Finally, we compared by paired *t*-test the accuracy of age prediction using only one symphyseal surface and using the system described above (results of right and left symphyseal surfaces matched) to the Suchey-Brooks method. All analyses were carried out using SPSS (Chicago, IL) software.

RESULTS

The working sample of 74 pubic bones was representative of the whole collection even when these were broken down into age groups.

Measured data from selected variables according to age and the main features of the univariate linear regression analysis for each one are, respectively, reported in Figure 4.

Results from the univariate linear regression analysis for each distance, measured using invariant descriptors for gray-level images, are not helpful, but their regrouping through a multiple linear regression analysis is strikingly efficient, as shown in Figure 5 (R square = 0.31, $P < 0.0001$).

We applied a multiple linear regression analysis to the 12 distances and the local variables which were stratified into two groups according to ridging: peak $\leq$0.05 mm ($n = 61$, R square = 0.57, $P <$0.001) and peak $>$0.05 mm ($n = 87$, R square = 0.63, $P < 0.0001$). The local variables consisted of the progression of the ventral rampart, the angle of lipping, the mean and standard deviation of the gray-level distribution of the trabecular bone, and the peak and frequency of ridging.

The Suchey-Brooks method provides an age estimation with a standard deviation of 10.18 years (R square = 0.49), while our age prediction system using data from the right and left symphyseal surfaces gives a standard deviation of 7.30 years (R square = 0.74) (Fig. 5) and, with only one symphyseal surface, a standard deviation of 11.6 years (R square = 0.41).

DISCUSSION

The purpose of this study is to improve the accuracy of age estimation at death using pubic bone analysis while at the same time avoiding lengthy bone preparation time and damage to the anatomical parts studied. The Suchey and Brooks approach involves quite a conservative preparation method which lasts 2 years.

A 3-D numerical data base made up from 74 well-documented pubic bones was the first step towards carrying out numerical data processing and mathematical model testing. We found significantly related age variables, some of which originated from the Suchey-Brooks analysis. Others were specifically taken from numerical data processing, such as the original shape comparison system provided by invariant descriptors for gray-level images.

The system of age prediction obtained from two symphyseal surfaces by multiple linear regression using these variables is characterized by an R square correlation coefficient of 0.74. This provides a notable improvement in age-estimation accuracy at death compared to the reference method applied to our collection sample. Indeed, in the plot for estimated age against actual age (Fig. 5), the dispersion of the points around the bisecting line decreases using our method. The standard deviation is 10.18 years and 7.3 years for the Suchey-Brooks method and our method, respectively. Our approach requires the use of the following 18 variables: the progression of the ventral

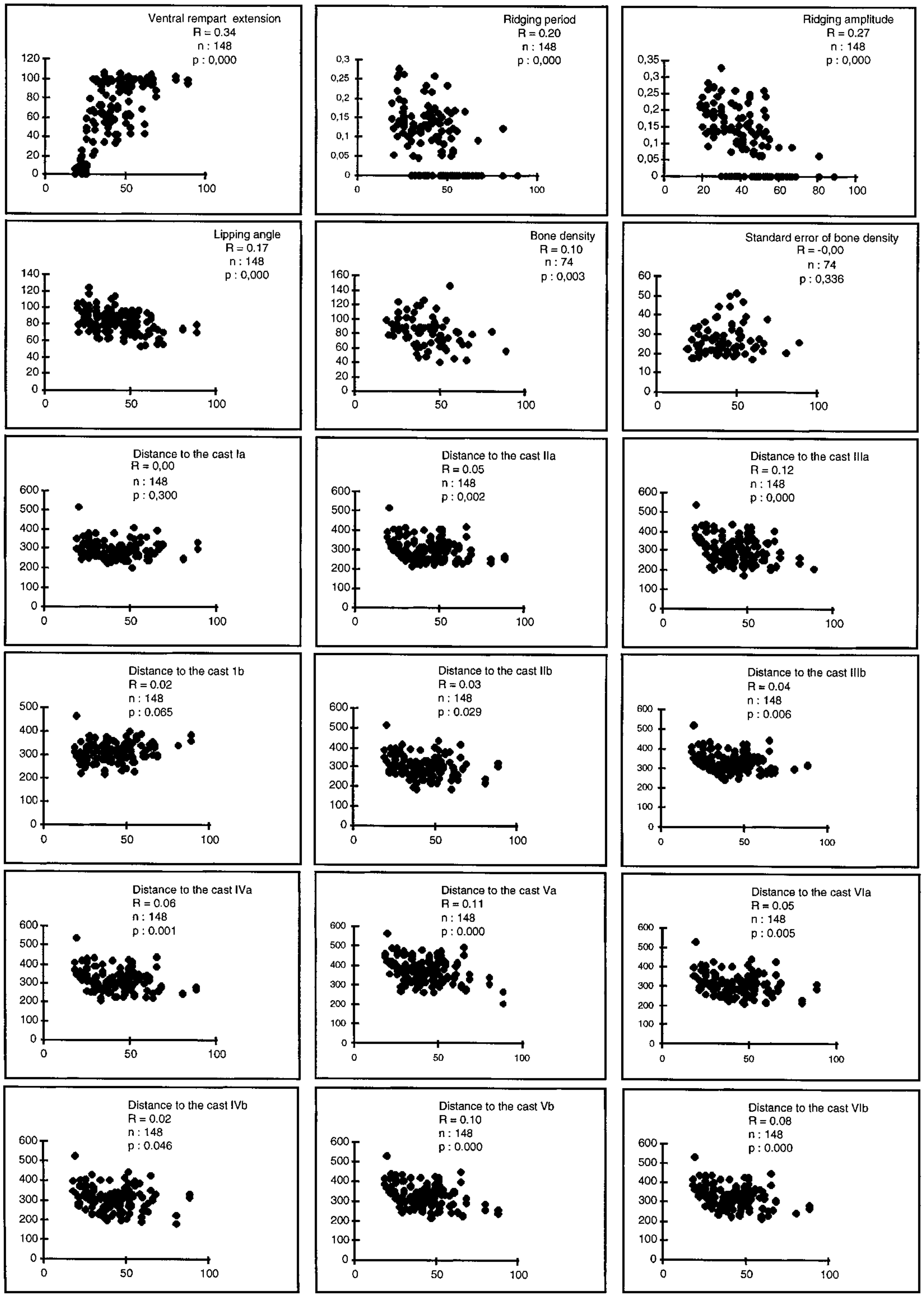

Fig. 4. Plot of parameter values against actual age. n, number of cases; *P*, significance of F; R, adjusted R square of linear regression.

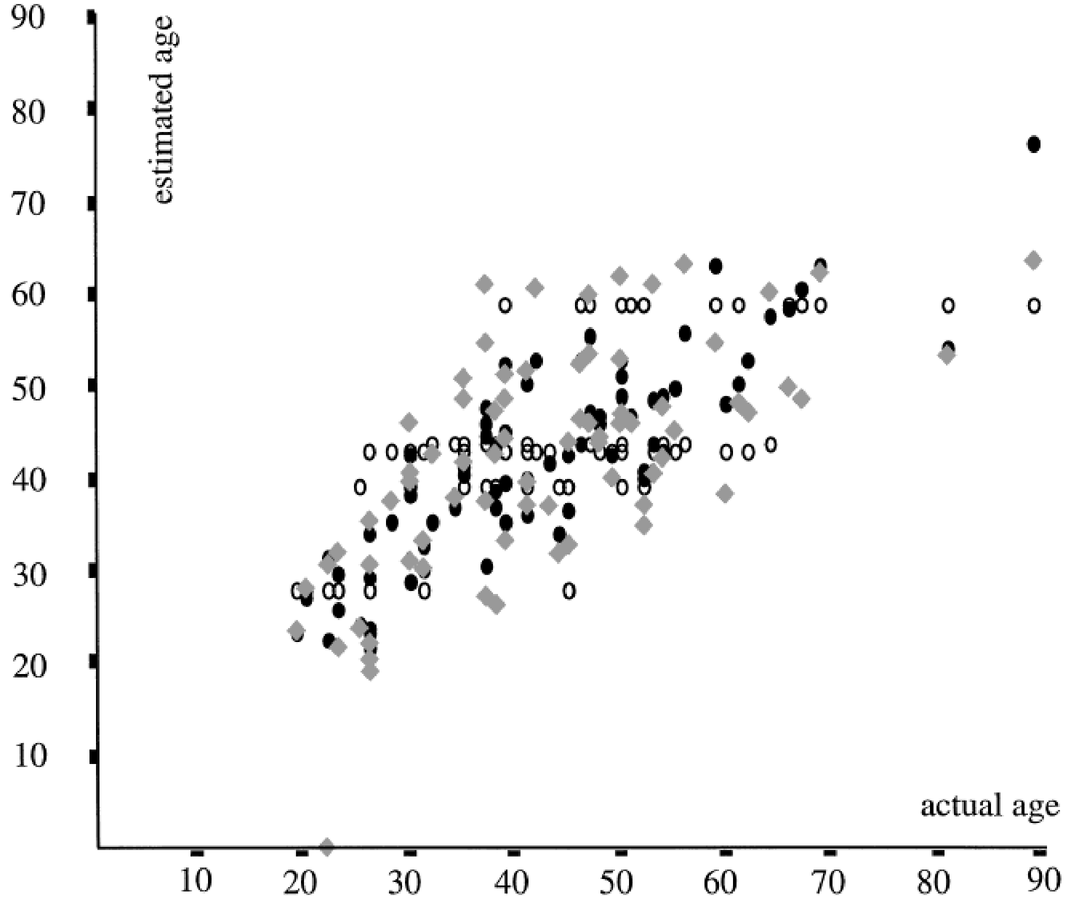

Fig. 5. Plot of estimated age against actual age by the Suchey-Brooks method with right and left symphyseal surfaces (open ovals), our method with only one symphyseal surface (shaded diamonds), and our method with right and left symphyseal surfaces (black ovals). The prediction of age by Suchey-Brooks method consists of the mean age of the obtained phase (calculated from our collection data).

rampart, the angle of the lipping, the peak amplitude and the frequency of ridging, the mean and standard deviation of the gray-level distribution of the trabecular bone, and the 12 distances measured using the invariant descriptors for gray-level images.

The invariant descriptors play an important role. A multiple linear regression analysis based on only 12 distances provides an R square of 0.31. Invariant descriptors take into account changes in external contours of the symphysis shape, which are particularly pronounced in the oldest age phases. Among the local parameters, only lipping characterizes these phases, and both ridging and ventral rampart progression appear as partially redundant criteria with respect to young phases.

The accuracy of our method could be further improved. For example, the concavity of the symphyseal surface is a discriminant feature between phases IV and VI of the Suchey-Brooks classification. Thus, the study of the curvature of the symphyseal surface should help us quantify this variable automatically. Furthermore, image resolution obtained by CT scan is limited for high definition. However, with a fractal model to characterize the trabecular bone, a much more accurate result could be achieved. Thus, the accuracy of the estimation of age at death based on the analysis of the pubic

bone may be improved by using numerical images. We note that the equation of age prediction obtained by multiple linear regression is valid for male corpses or skeletons only. Further study needs to be undertaken on female pubic bones. With respect to the potential application of our findings, a pubic symphysis image segmentation is required to avoid lengthy bone preparation time, especially in forensic cases. Finally, some relevant parameters have not been studied and might perhaps enhance the performance of our age at death prediction system. We point out that the invariant descriptors with respect to translation, rotation, and scaling could play an important role regarding the description of anatomical shapes in anthropology.

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